Response of Asymmetric Slim Floor Beams in Parametric-Fires

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ABSTRACT

State-of-the-art slim floor systems are a newest addition to the composite construction industry and several types are currently being used for building and construction purposes. Asymmetric slim floor beams are a type of slim floor systems which consist of a rolled section with a larger bottom flange. The larger bottom flange induces asymmetry and offers an efficient use of the material strength as a composite beam. It also offers a larger area to support the steel decking and pre-cast slab units during the construction of floor. Experimental and analytical investigations on response of asymmetric slim floor beams have shown that these beams offer a higher fire resistance in comparison to the conventional composite systems with down-stand steel beams. Previous investigations on these beams have been conducted in standard fire exposure conditions, hence, their response to natural fire scenarios still deems further examination. This study addresses response of asymmetric slim floor beams in natural fire exposure conditions. For this purpose, finite element models developed and verified by the authors are employed to study the thermal and structural response of slim floor beams in fast and slow parametric-fire exposures. Results obtained show that the asymmetric slim floor beams behave differently in parametric-fires in comparison to that in standard fire exposure conditions. Asymmetric slim floor beams continued to support the loads for the whole duration of parametric fires without undergoing excessive deflections and offering a better fire resistance. Unlike in case of the standard fire where the temperatures keep on increasing throughout the duration, temperatures on the slim floor beams decrease after reaching a maximum point in parametric-fires. It was found that for fast parametric-fires, the thermal gradient across the section is more severe as compared to that for the slow parametric-fires at earlier stages of fire exposure. In case of the fast parametric-fires, the rise and fall of temperatures on the slim floor beams are rapid while in case of the slow parametric-fire, these variations in temperatures are subtle. It was observed that the structural response of slim floor beams in standard and parametric fires depends on the average temperature across the steel section. Deflections predicted for the beams were found to be directly related to these average temperatures. Outcomes of this study will benefit in understanding the response of asymmetric slim floor beams in natural fire conditions and will aid to develop simple fire design methods for future use.

KEYWORDS:

Asymmetric slim floor beams, fire resistance, natural fires, finite element modelling, structural response, thermal response.

INTRODUCTION

Response of slim floor beams at elevated temperatures deems for detailed investigations because of their abundant use in high rise buildings and car parks [1]. Slim floor beams offer shallower depths as compared to the traditional composite beams, as a result, they help in reducing the depth of floors and height of the structures. These beams consume lesser construction materials due to their reduced height which reduces the cost of construction. Combination of slim floor beams with composite steel decking offers a faster method of construction as well as an easy passage for electric and mechanical networks [2]. Most part of the steel section in such beams is encased within the floor concrete except for the bottom flange, hence, these beams offer a higher fire resistance being protected from flames and direct exposure to heat [3]. Response of slim floor beams has previously been investigated through several experimental [4] and analytical investigations [5] [6]; they are yet limited to standard fire exposures.

This study addresses the response of asymmetric slim floor beams (ASBs) in parametric fires; a representation of the natural fires, through analytical investigations. During previous investigations by the authors, behaviour of the slim floor beams at elevated temperatures has been replicated and verified against the test data and the verified finite element (FE) models are further used to perform sensitivity studies [5][6]. Here, these verified FE models are used to simulate the response of slim floor beams against natural fires in terms of parametric-fires given in the Eurocodes [7]. As the steel beam is partially protected by the concrete and only the bottom flange is exposed to fire, significant thermal gradients are developed across the section and thermal bowing is evident. The parametric fires selected during this study are a representation of a wide range of natural fires expected in an office compartment.

AIMS AND OBJECTIVES

This research is instigated with the purpose to explore the response of asymmetric slim floor beams in parametric-fires, a representation of the natural fires. To achieve this, thermal and structural response of asymmetric slim floor beams is investigated in two natural fire scenarios, a fast fire and a slow fire. Response of asymmetric slim floor beams is then analysed in comparison with that in standard fire exposure conditions and differences in their behaviour are highlighted. During slow fire exposures, it is expected that more uniform temperatures will develop, while in fast heating exposures, extreme thermal gradients are expected. As the temperature profile of the steel beam is important and affects their fire resistance, behaviour of the slim floors exposed to natural fires must be investigated.

RESPONSE OF ASBs IN NATURAL FIRES

The Natural Fires

Most of the investigations on the response of slim floor beams are performed against the standard fire exposures. In this study, response of the slim floor beams is assessed against the natural fires in terms of parametric-fires as recommended by the Eurocodes [7]. The parametric-fire curves representing the natural fires are in terms of a fast and a slow parametric-fire as shown in Fig. 1.
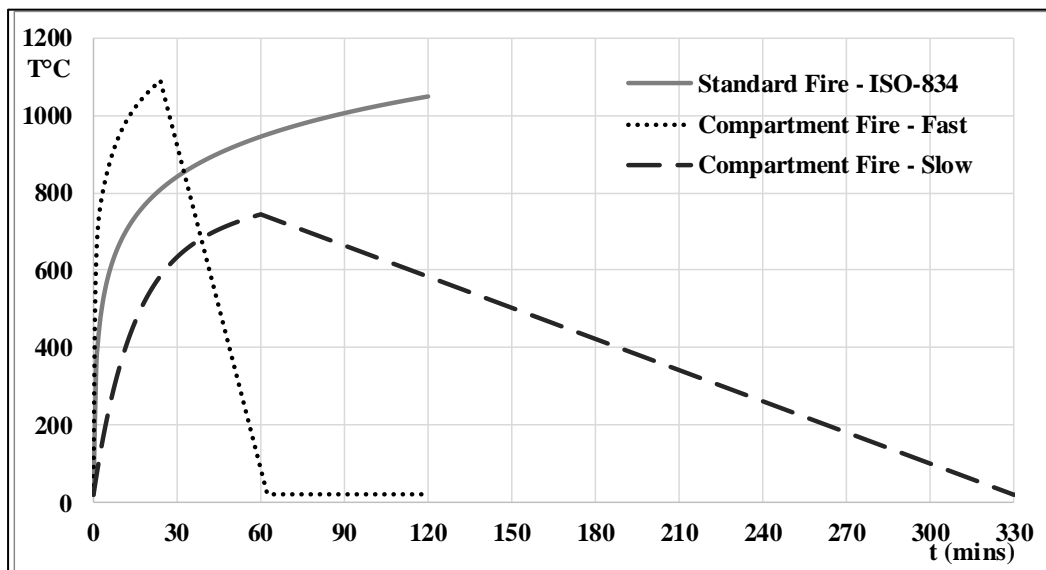

Fig. 1. Parametric and standard fire curves

For both fire scenarios, the design value of fire load density ($q_{t,d}$) is taken as 200 MJ/m^2, considering the compartment to be a representative of an office building. The 'b' factor, which is the representation of the density, specific heat and thermal conductivity of compartment boundaries, is taken as 1120 J/M^{2}s$^{1/2}$K. Values of the design fire load density and that of factor 'b' are kept similar for both fast and slow parametric-fires. Value of the opening factor for the slow fire is taken as 0.02m$^{1/2}$; minimum value recommended in the Eurocodes [9] while that for the fast fire is taken as 0.1m$^{1/2}$. These parametric fires cover a wide range of the natural fires thus enabling a general applicability of the findings from this research. Parametric fire curves and the standard fire curves used in this research are produced using the equations proposed in the Eurocodes, [7].

Finite Element Modelling

Response of asymmetric slim floor beams to natural fires is investigated through finite element modelling (FEM) using ABAQUS [8]. Their response at elevated temperatures is replicated and verified by the authors previously using the FEM and various parametric studies have also been performed using these verified models [5][6]. In this study, the same FE models are used to simulate the response of a slim floor beam assembly 5000 mm long having a span of 4500 mm between the supports. The beam assembly consists of an ASB-280 rolled steel section and a composite slab constructed using normal weight concrete and deep steel decking. The beam assembly is 308 mm deep and has a width of 950 mm as shown in Fig. 2. This beam assembly is similar to the one used previously during an experimental investigation [4]. During the FEM, half of the beam assembly is modelled while the support and boundary conditions are kept similar to those reported for the test except for the fire exposure conditions [4]. Non-linear thermal and mechanical properties of concrete and steel are adopted from the Eurocodes [9][10]. Further details of the two-step FEM method used in this study are available in previous research publications by the authors [5][6].
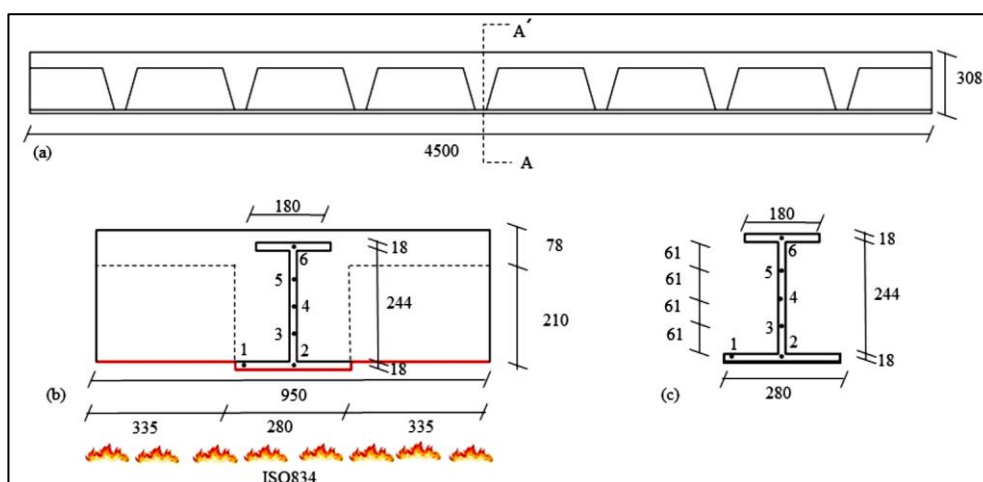

Fig. 1. Details of the test assembly, (a). Side elevation, (b). The section at AAˊ, (c). Cross-section of steel beam

Three investigations, one each against the standard fire, the slow parametric-fire and the fast parametric-fire are performed. Applied loads during the structural analyses are kept equivalent to a degree of utilization of 0.55 of the steel beam section. This degree of utilization gives a representation of the maximum expected external loads in any fire case scenario [11].

Results and Discussion

Thermal predictions obtained from the FEM analysis are depicted in Fig. 3. Thermal predictions for the flanges are shown in Fig. 3(a) where location 6 represents mid-point of the top flange while location 1 represents the one on edge of the bottom flange. Thermal predictions for the top flange are similar for all fire exposures and remain within 200°C for 120 mins. The top flange being far from exposed surfaces is least influenced by the fire exposure type. On the other hand, parts of the beam closer to the exposed surface are most influenced by the exposure type. In case of the standard fire exposure, temperatures on thermocouple 1, on the bottom flange, keep on increasing and reach 550°C, 800°C, 950°C and 1000°C after 30, 60, 90 and 120 mins of heating, respectively. For the fast parametric-fire, temperatures at this location are 850°C and then decrease to 450°C, 230°C, and 150°C for the same duration of exposure. In case of the slow parametric-fire, temperatures on the bottom flange gradually increases to 600°C after 76 mins and slowly decrease afterwards to 587°C after 120 mins. For thermocouple position on the middle of the steel web, position 4, the predicted temperatures continue to rise for standard fire exposure as shown in Fig. 4(b). For fast-parametric fire, these temperatures increase for the first 65 mins and then gradually decrease while for the slow and natural fire

exposure conditions, temperatures at this location continue to rise for 120 mins as shown in Fig. 4(b). These temperature differences highlight the effect of exposure conditions on the thermal behaviour of slim floor beams and suggest their behaviour is highly fire-exposure dependent.
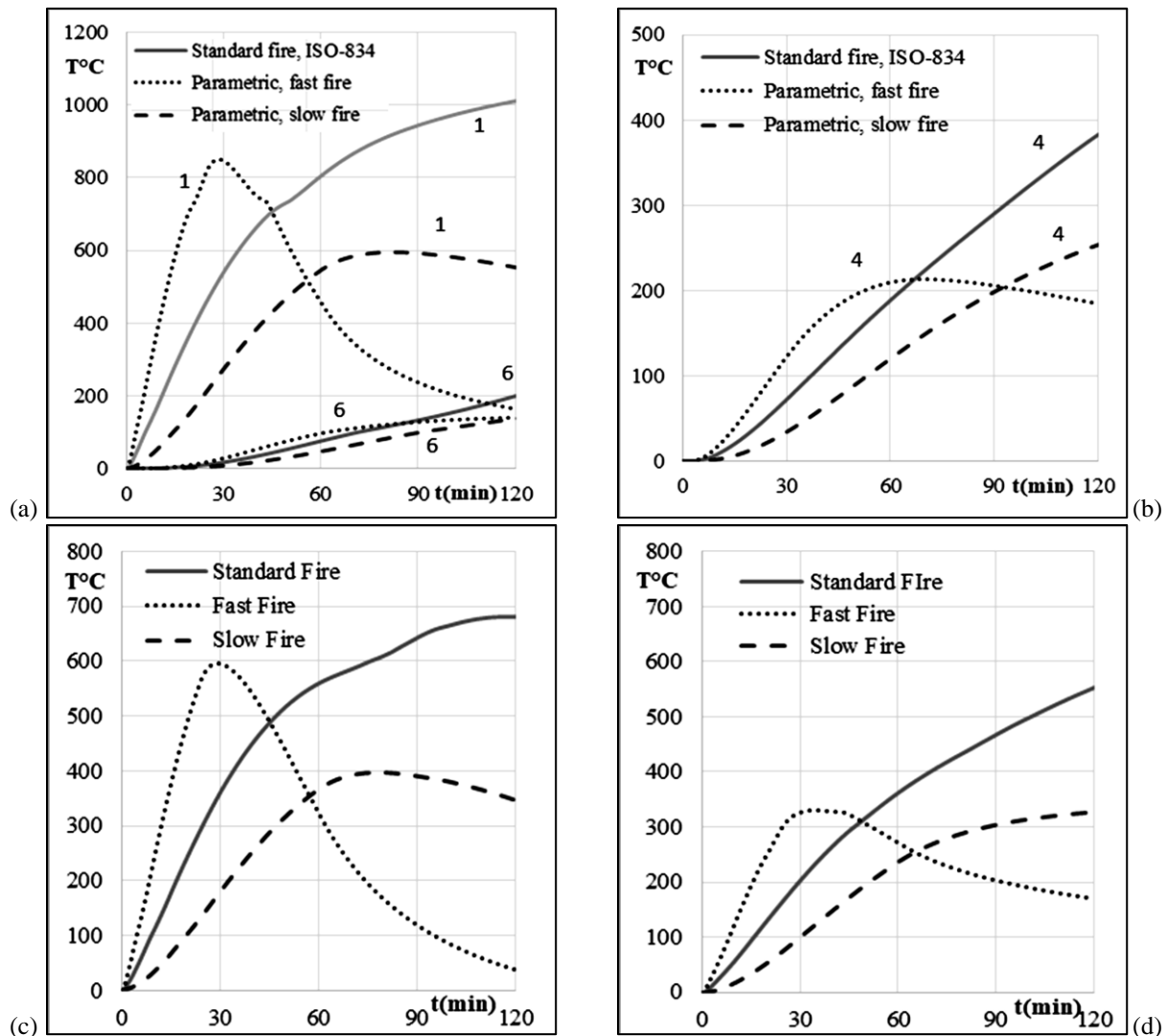

Fig. 2. Comparison for thermal results for standard and parametric fires: (a) thermal predictions for flanges, (b) thermal comparisons for the web, (c) thermal gradient and (d) average temperatures across the steel-section

Thermal gradient across the section of the slim floor beam was momentous as it has been reported previously for various slim floor beam types [4][5][6]. Based on the fire scenarios, distinct thermal gradients were observed across the beam during this study. The thermal gradients in terms of the temperature difference between thermocouple positions 2 and 6, middle of the bottom and the top flange, are presented in Fig. 3(c). For the first 45 mins of fire exposure, the thermal gradient for fast fire is the greatest with a maximum temperature difference of 598°C after 30 mins. This thermal gradient gradually decreases and reduces to 50°C after 120 mins of fire exposure. In case of the standard fire, thermal gradient across the section increases throughout the duration of heating. For the slow parametric-fire, this thermal gradient is the least of all three fire exposure types for the initial 56 mins. Beyond this point, the thermal gradient for slow fire becomes higher than that predicted for the fast parametric-fire as shown in Fig 3(c).

Like the thermal gradient, average temperatures on the steel section were also found to be variable for different fire exposures. The average temperatures shown in Fig. 3(d) are taken from the predicted temperatures for six thermocouples shown earlier in Fig. 1(c). In case of standard fire, the average value of temperatures keeps on rising for the whole duration of fire exposure while for the parametric fires, these temperatures decrease after reaching a maximum value. For the first 48 mins of heating, the average temperatures are higher for the fast parametric-fire and then gradually reduce onwards. Like the thermal gradient, average temperatures are the lowest for the first 65 mins of heating for the slow parametric-fire. Average temperatures for the slow fire keep on increasing and overtake those predicted for the fast parametric-fire beyond 65 mins. The thermal gradients and average temperatures on the section can also be

seen in Fig. 4 after 120 mins of fire exposure. For standard fire, the thermal gradient as well as the predicted temperatures across the section, are the highest (Fig. 4(a)) while for fast parametric-fire, these are the lowest (Fig. 4(b)). As heating part of the curve for the slow parametric-fire is longer in comparison to that of the fast-parametric fire, at 120 mins, the temperature gradient and the predicted temperatures are higher for slow fire in comparison to the fast parametric-fire as shown in Fig 4.
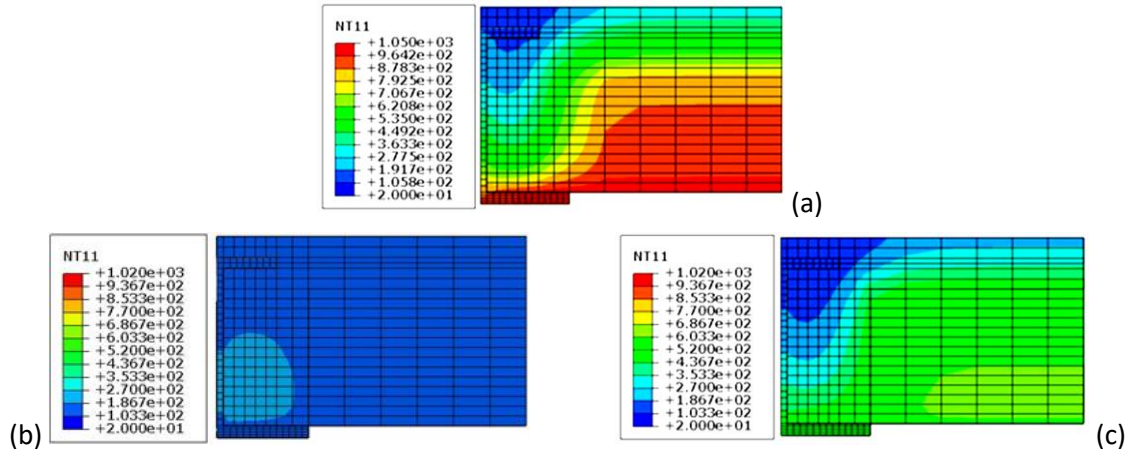

Fig. 3. Temperatures contours after 120 mins of fire exposure for: (a) standard fire, (b) fast fire and (c) slow fire

Structural response of the slim floor beam assembly is analysed in terms of the mid-span deflection predicted for the standard and the parametric fire exposures. The failure criteria adopted here are deflection-based and in terms of the maximum deflection and maximum rate of deflection given by the British Standards [12]. It is seen in Fig. 5 that the slim floor beam assembly in standard fire conditions exceeds the deflection rate limits after 74 mins of heating. In case of the fast parametric-fire, the maximum mid-span deflection was predicted to be 94 mm after 38 mins of heating. Beyond this point, the deflection reduced and became 62.5 mm after 60 mins and then further reduced to 25.5 mm after 120 mins. For the slow parametric-fire exposure, the predicted mid-span deflection was 28 mm after 30 mins while the maximum predicted deflection was 59 mm after 83 mins. This deflection reduced to 54 mm after 120 mins of heating as shown in Fig. 5. For both parametric-fire exposures, neither limits of the deflection were reached, and the slim floors outlasted the whole duration of fire without failure. These results show that the structural behaviour of slim floor beams evidently has a direct dependence on the average temperatures. For instance, the average temperatures across the section keep on increasing for standard fire and the predicted mid-span deflection follows the same. Likewise, the average temperatures as well as the deflections are higher for the first 33 mins for the fast parametric-fire and reduce afterwards. Similar relationships are seen for the slow parametric-fire as well. This suggests that the structural response of slim floor beams is a function of the average temperatures across the steel beam section.
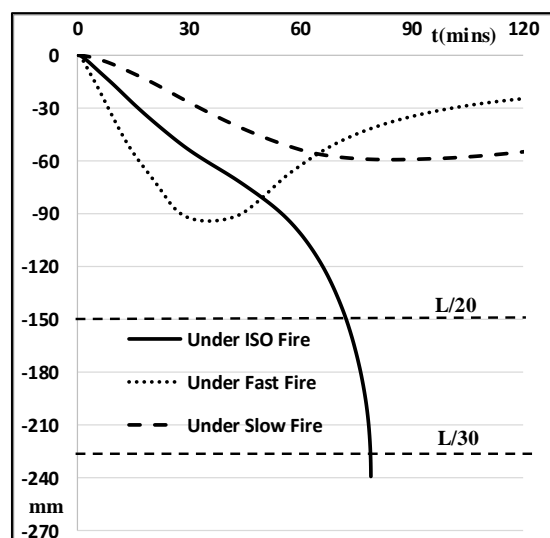

Fig. 4. Mid-span deflections for different fire exposure conditions

CONCLUSIONS

This paper presents the findings of a computational study conducted to analyse the response of slim floor beams in natural fire exposure conditions in terms of the parametric-fires. The fire scenarios used during this study represent a wide range of possible fires, hence findings from this study have a general applicability. It is found that the exposure conditions have a significant influence on response of the slim floor beams in fire. In standard fires, temperatures of the assembly continue to rise throughout its duration while in parametric fires, these temperatures reduce after reaching a maximum value. Although the thermal gradient was high across the beam section for all fire exposures, the magnitude of this gradient was variable from one exposure type to another. The slim floor beam assembly outlasted the whole duration of the parametric-fires which suggests that these beams offer an improved fire resistance in real fire conditions. Variance in the thermal and structural response of the investigated slim floor beam against different fire exposures suggests that their behaviour in fire is highly exposure-type dependent. It is interesting to see a direct relation between the average temperatures on the steel beam and mid-span deflection. This affiliation suggests that the structural response of slim floor beams is a function of the average temperatures on the beam.

Authors of this research are currently working on devising simple fire design methods for slim floor beams. These fire design methods are expected to provide a relationship between the fire rating, the average temperatures, and degree of utilization of slim floor beams.

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